A Simplistic View of Hadron Calorimetry

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PDG
LBNL

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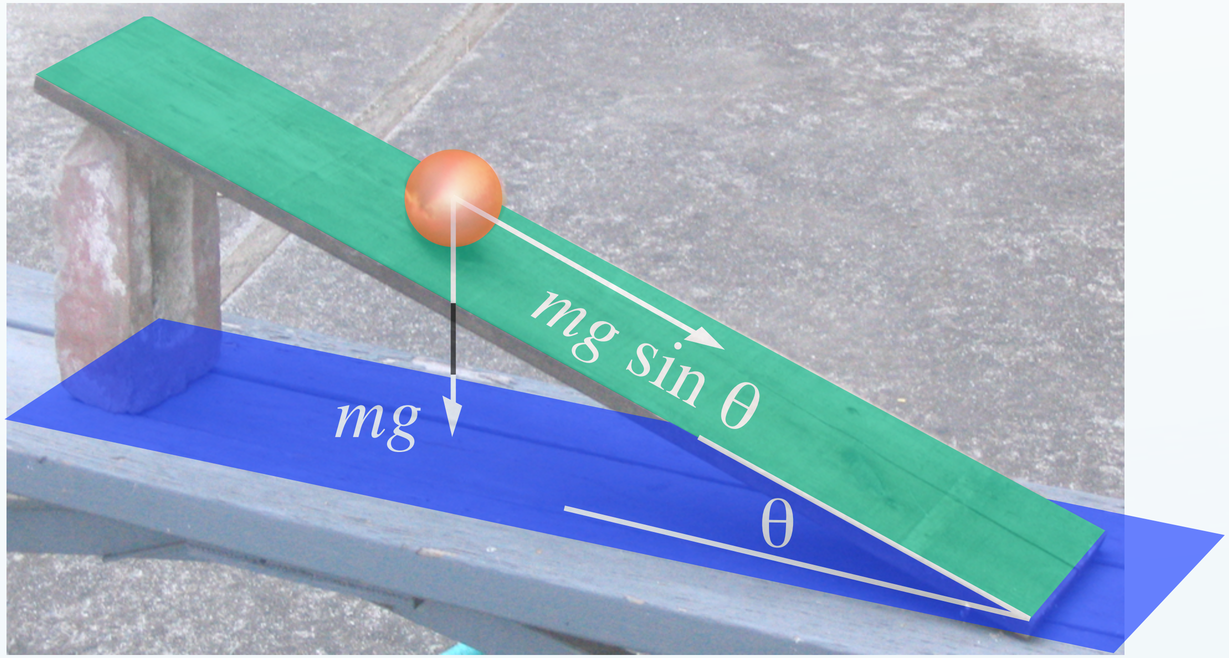
An example of my approach:

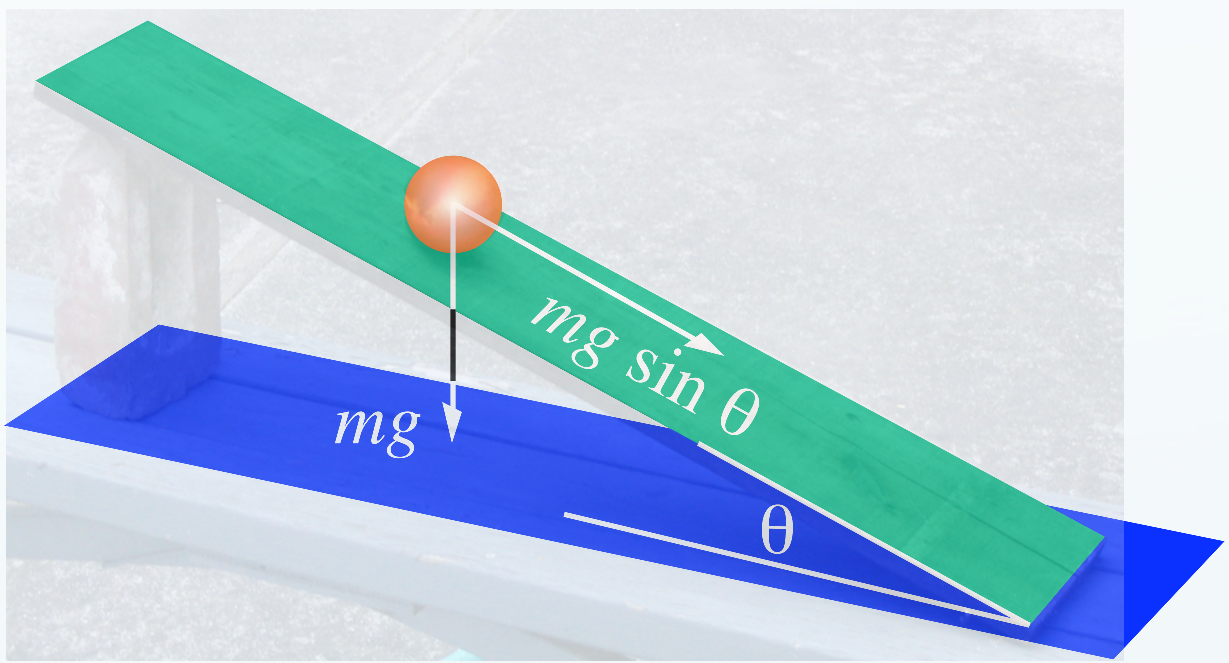
Suppose the problem is to describe the motion of the peach rolling down the bumpy board

OK, you are all physicists, and most of you have taught elementary physics labs

What you really see is:



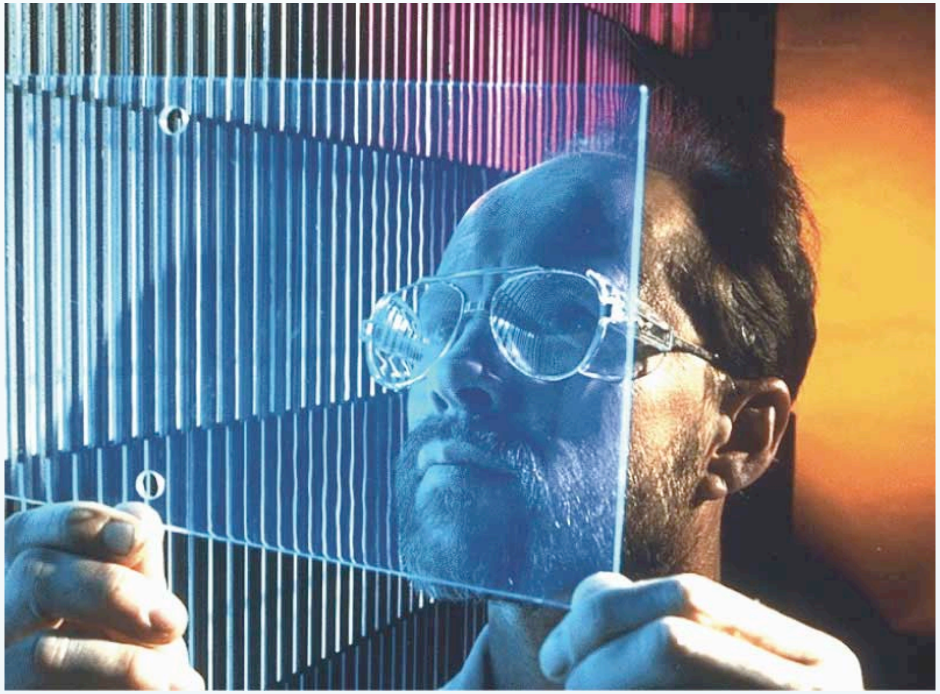
This you can solve!

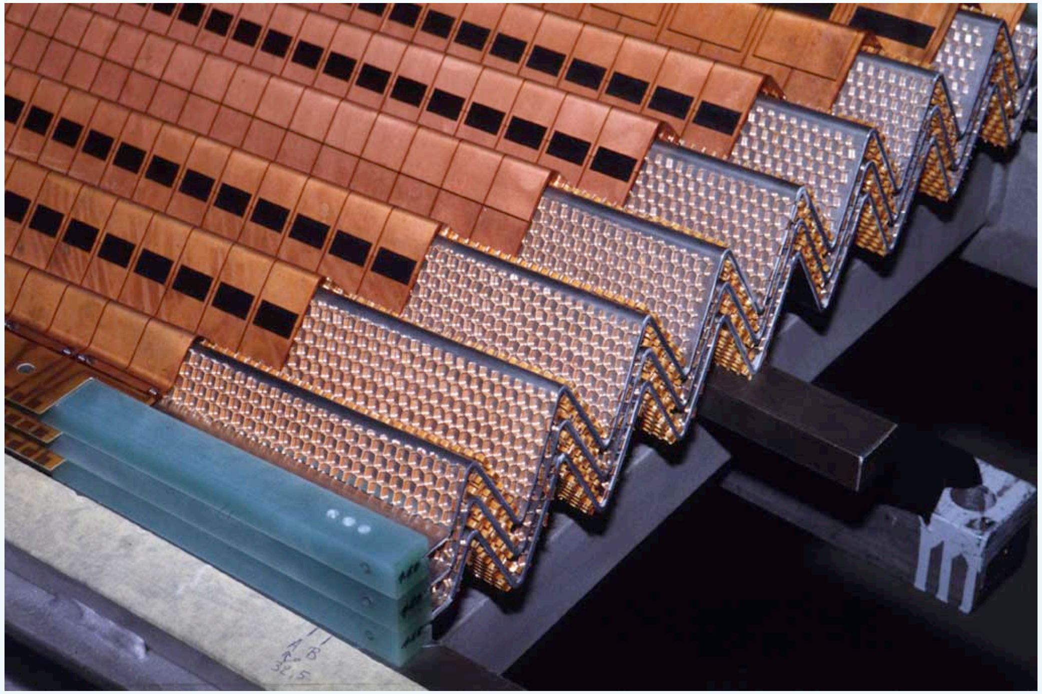


. . . and then go back and introduce the fuzz and bumps and things as corrections

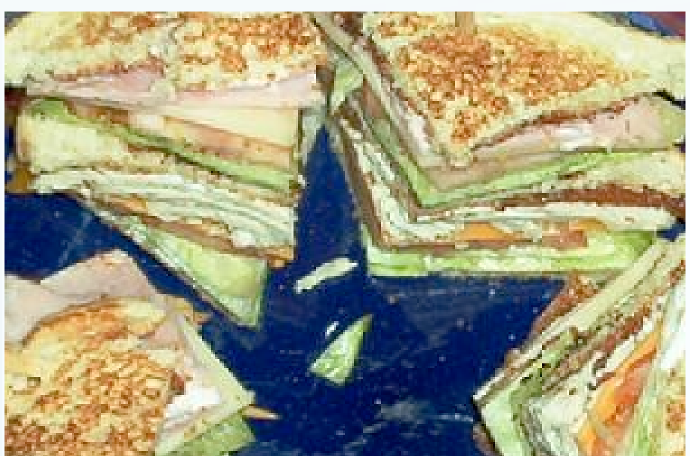
Early Caltech design for a hadron calorimeter

After more than four decades of R&D, calorimeters have become incredibly sophisticated, well-engineered
---and beautiful!

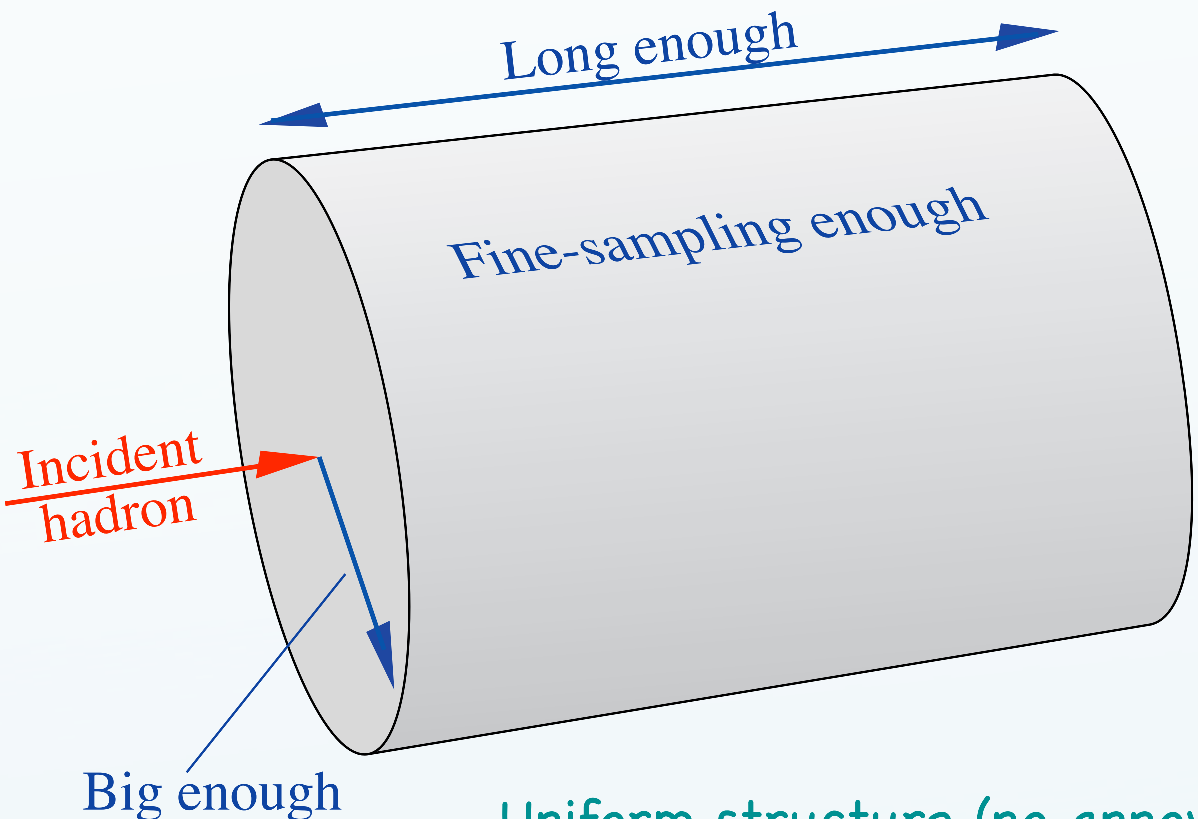




. . . and there are many, many design concepts

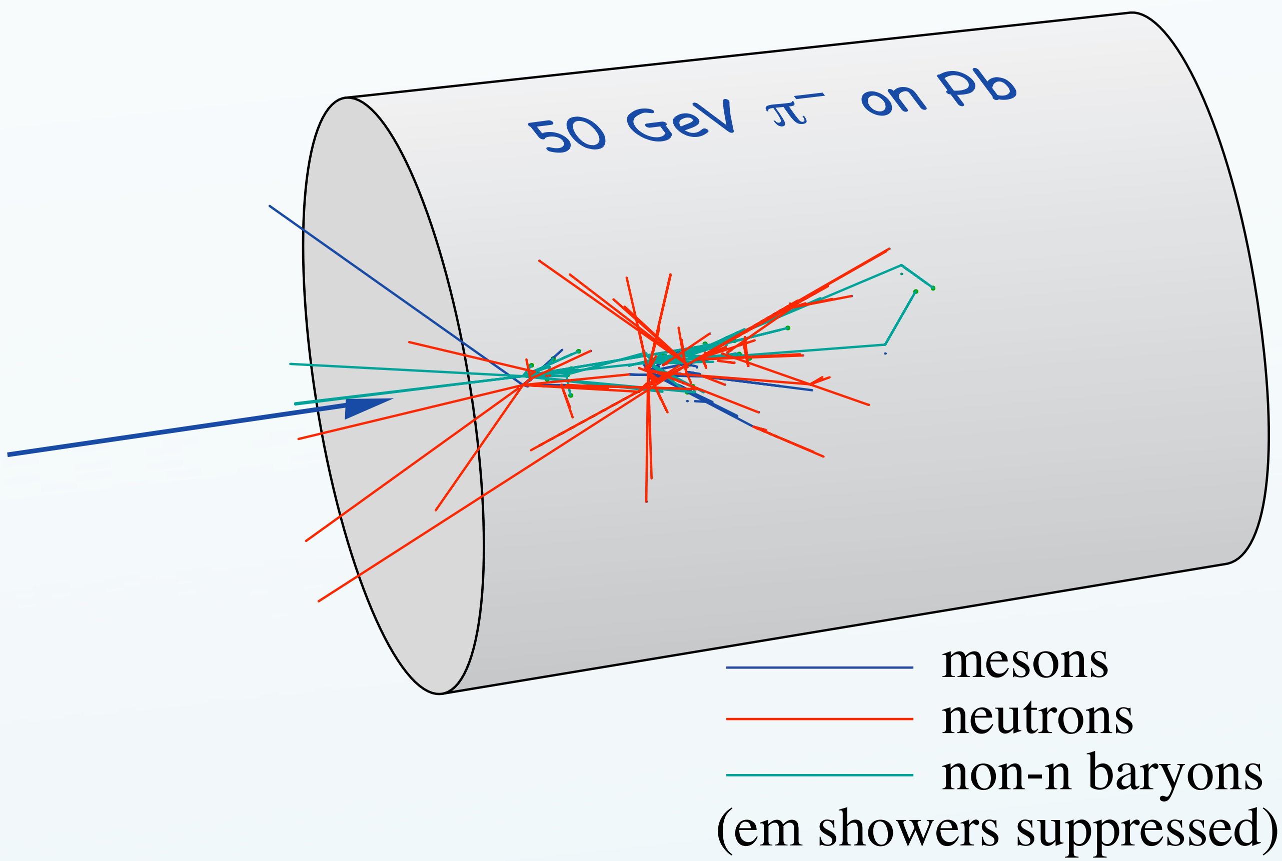


But, as with the inclined plane, I'll make some physicist-type approximations --



Uniform structure (no annoying EM compartment), big enough to contain any cascade, single particle axially incident!

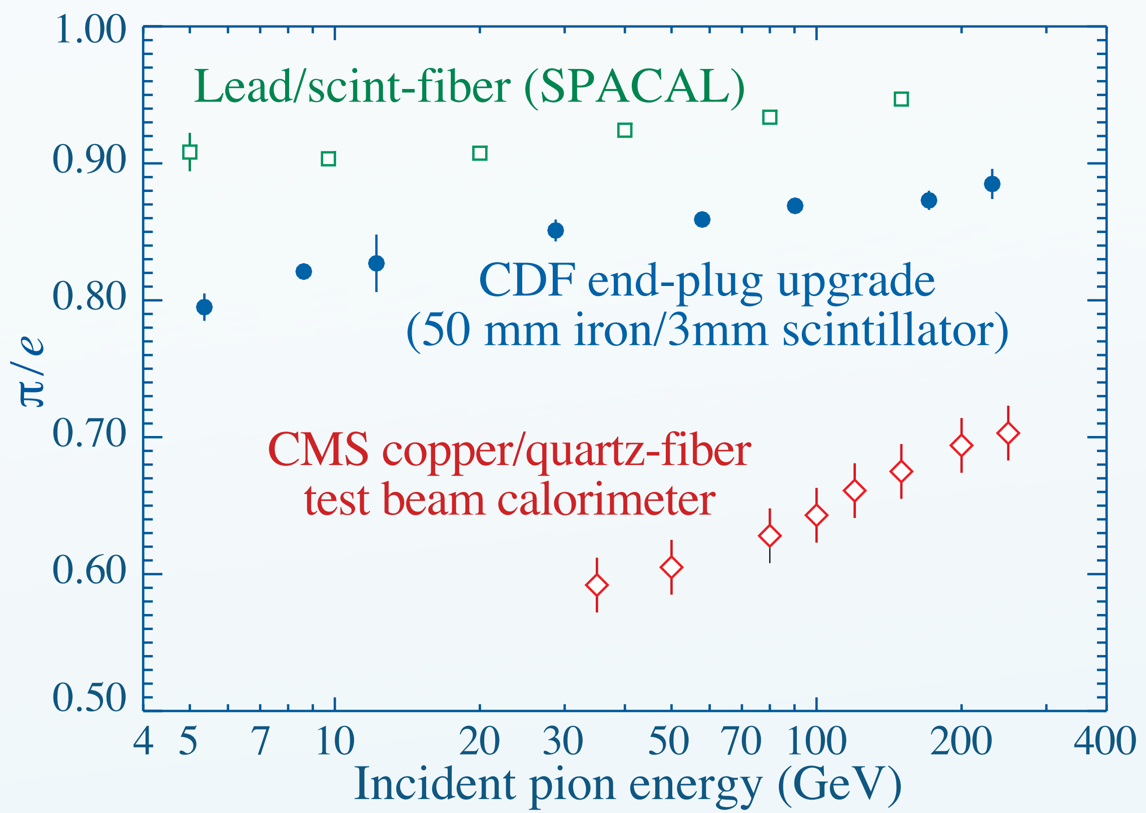
Even so, hadronic cascades are weird and individual. Low multiplicity, lots of neutrons, albedo (front-surface) leakage



So what's the object of today's colloquium?

For decades, people have been obtaining data like those shown below. Typically the energy scale of a test-beam calorimeter has been set by its linear response to electrons, which then calibrates the energy-dependent response to pions

CAN WE UNDERSTAND THE FUNCTION OF ENERGY THAT DESCRIBES THESE DATA FROM FIRST PRINCIPLES?



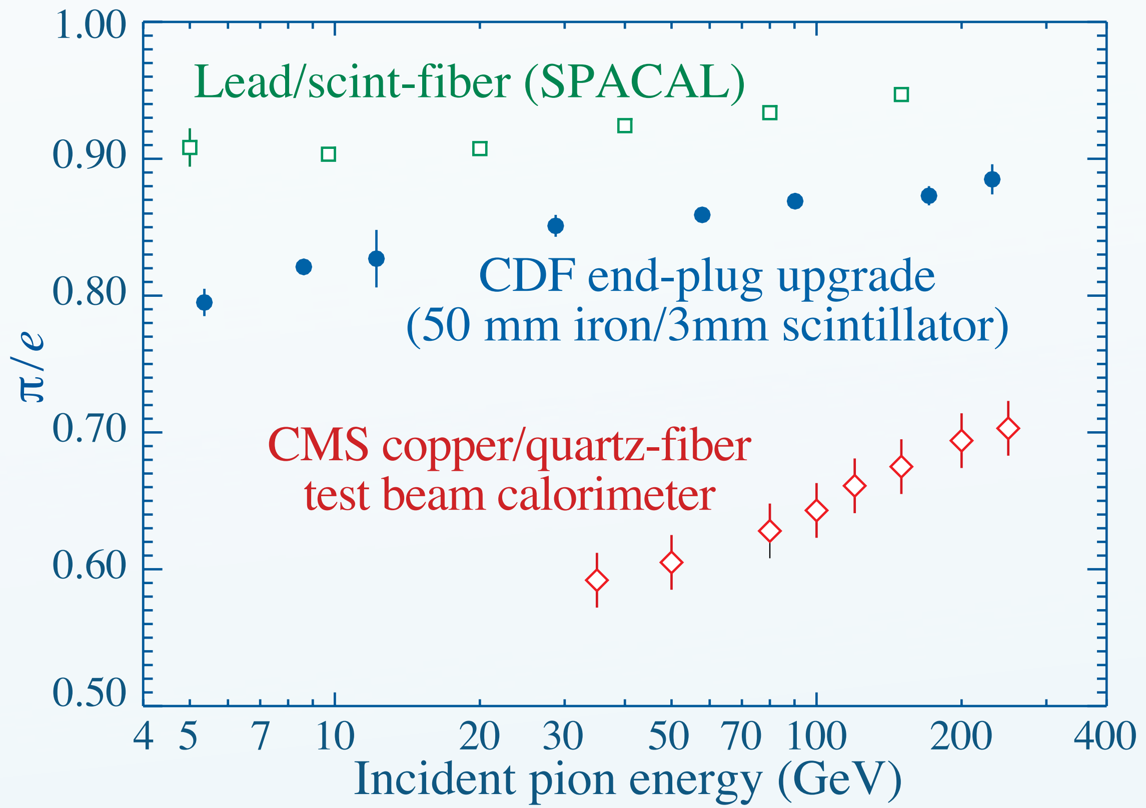
(DØ values are too close to 1.00 to be interesting)

Today's game plan:

- electron and hadron energy deposit
- π/e response ratio
  ✯ include nuclear gammas (new)

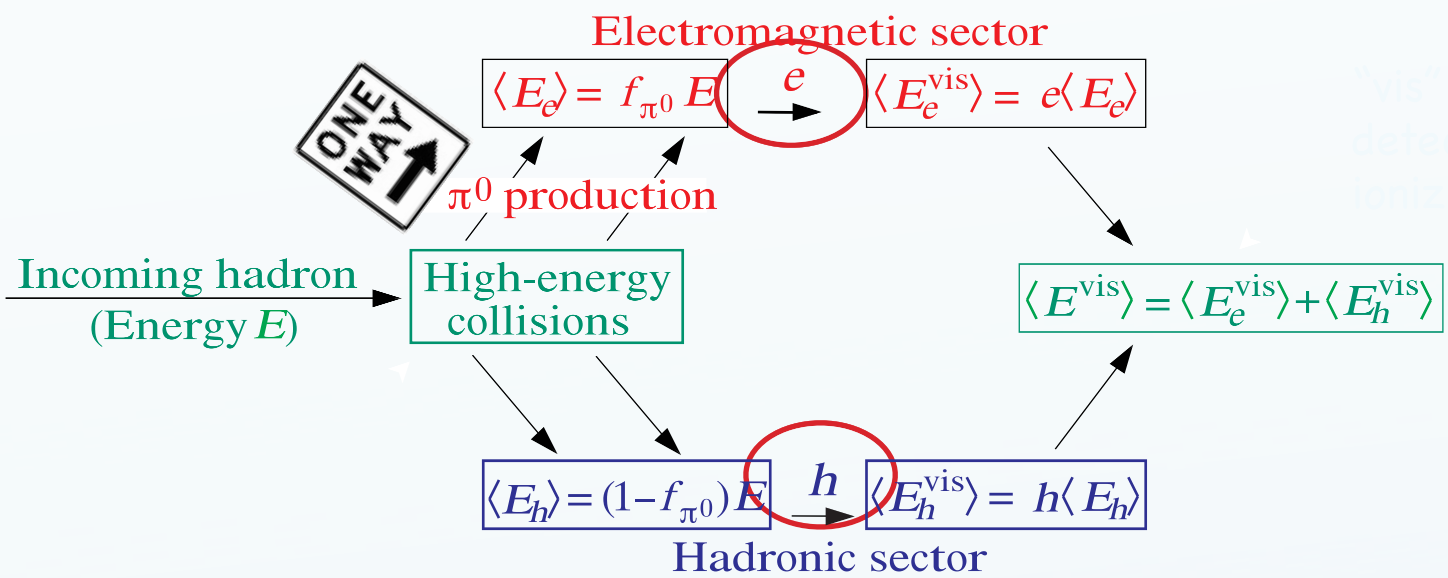
- Unrelated detour: $-dE/dx$

- p/π response ratio!
- Dual readout calorimeters and the future

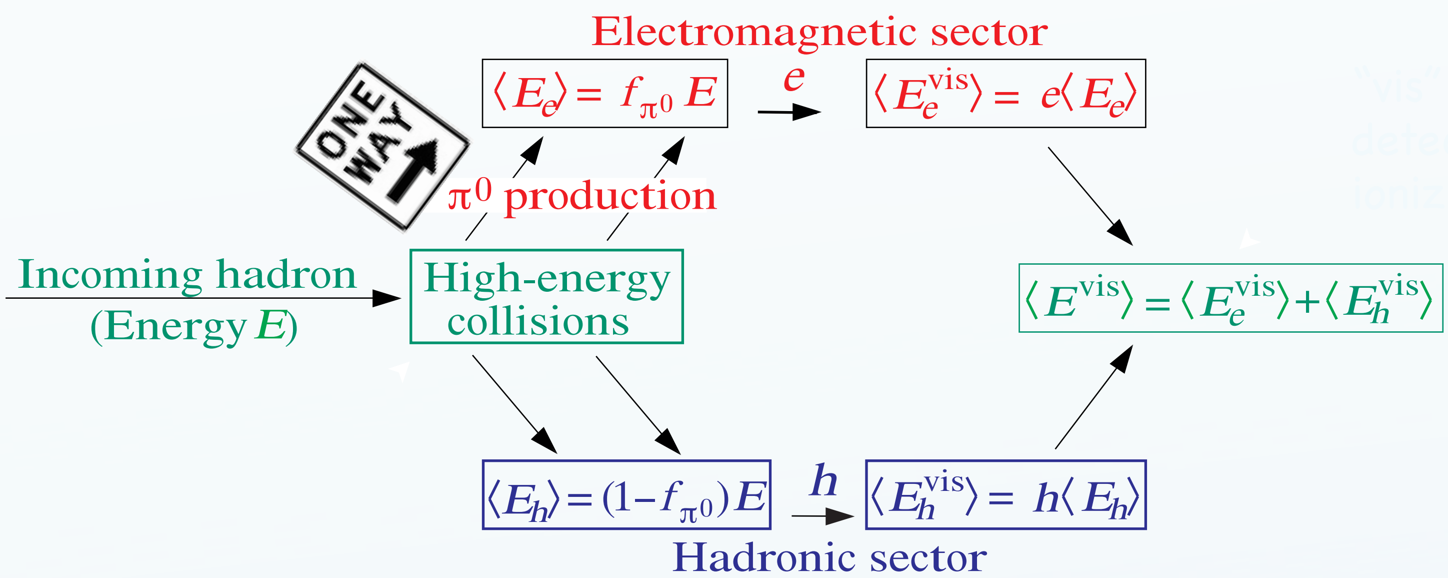


Energy is ultimately detected by measuring ionization.

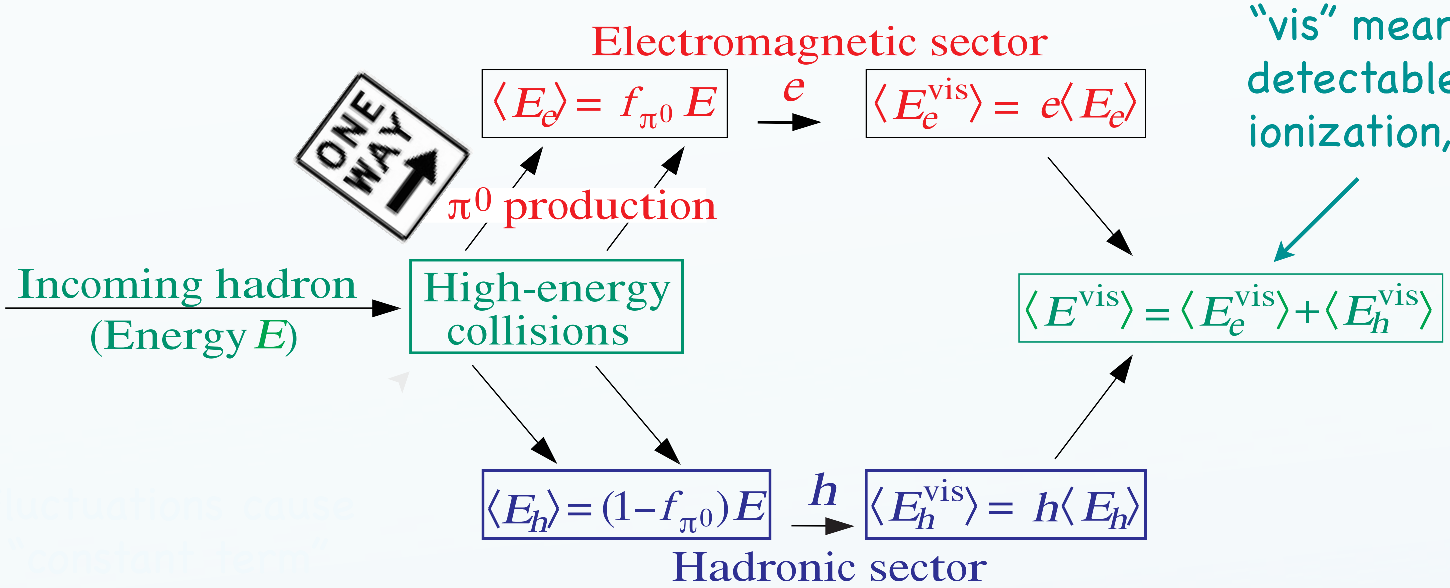
The trouble is that em and hadronic energy deposits are (usually) detected with different efficiencies:



hadronic energy fraction $f_h = (1 - f_{\pi^0})$ (definition)



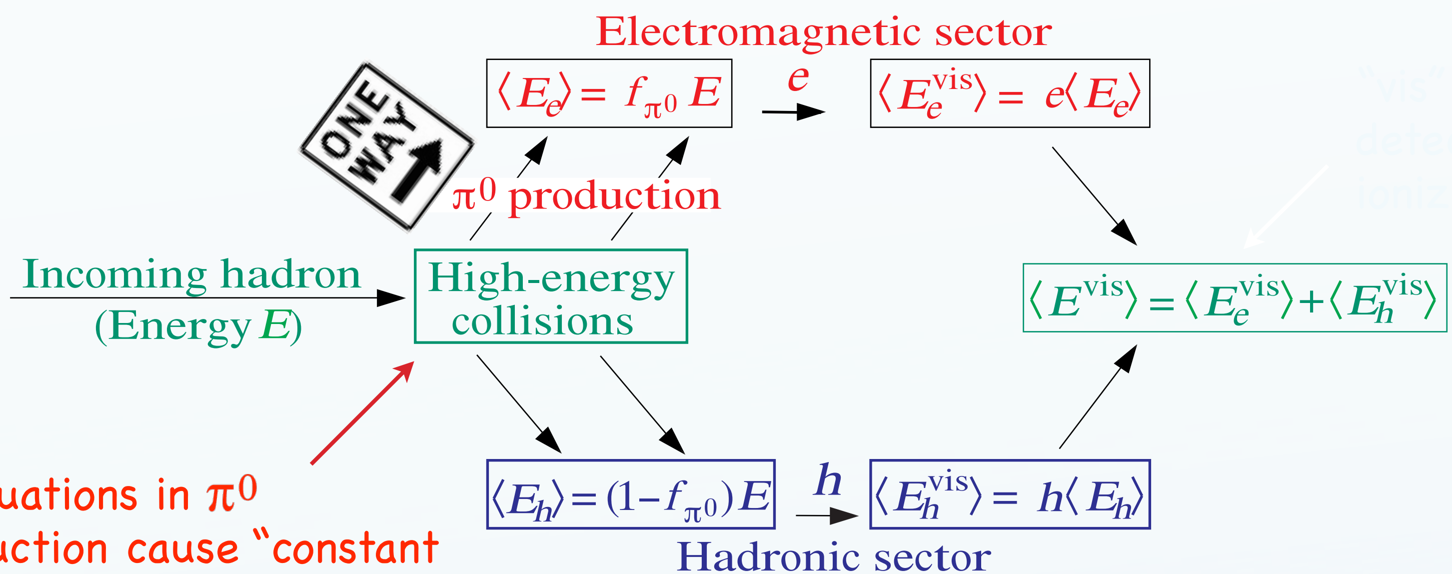
Spallation, low-energy ionizing particles and fragments, nuclear gamma rays, maybe fission, and things too fierce to mention



"vis" means potentially detectable light, ionization, or whatever

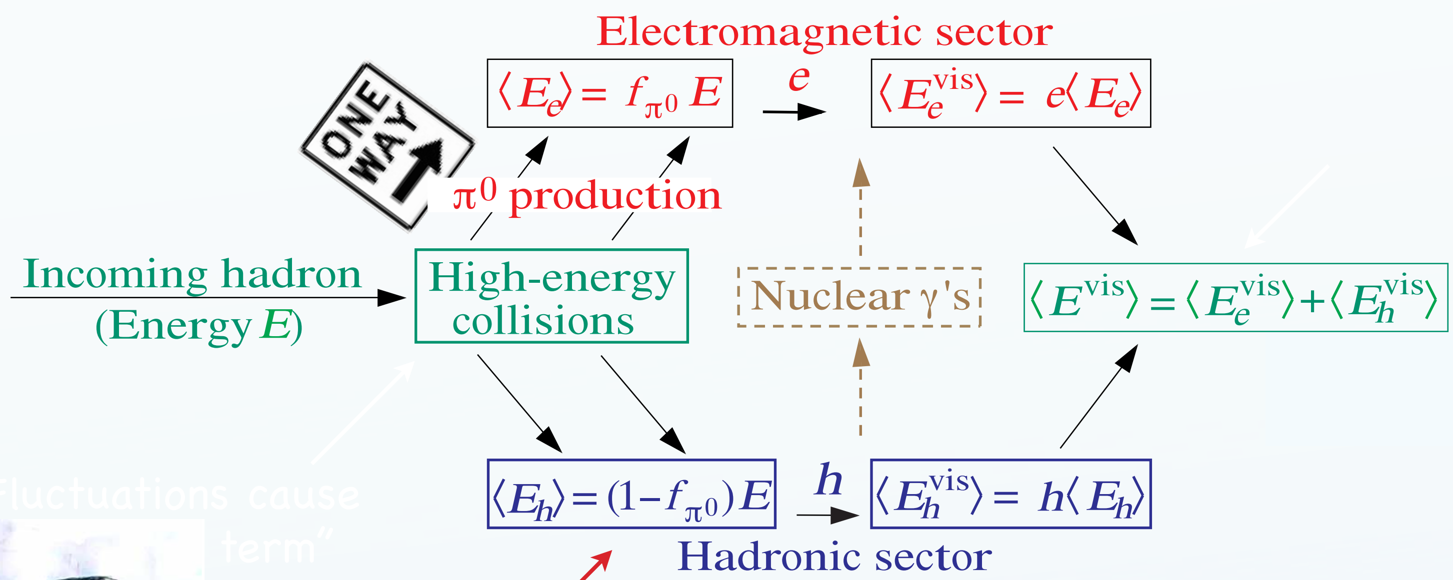
Resolution

An electromagnetic calorimeter is the gold standard



Fluctuations in π^0 production cause "constant term" in resolution

Fluctuations in neutron energy deposit dominate calorimeter resolution



Nuclear gamma ray energy scales as f_h, rather than f_{π^0}

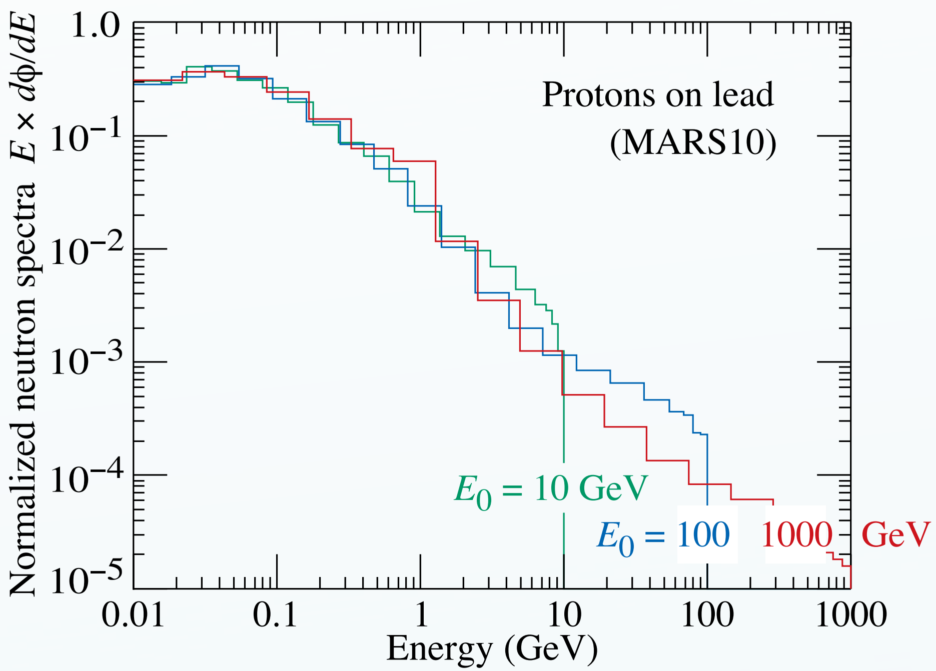
This doesn't change the picture I'll present; it just means that part of the hadronic signal, $f_h f_\gamma$, is detected with efficiency e instead of h

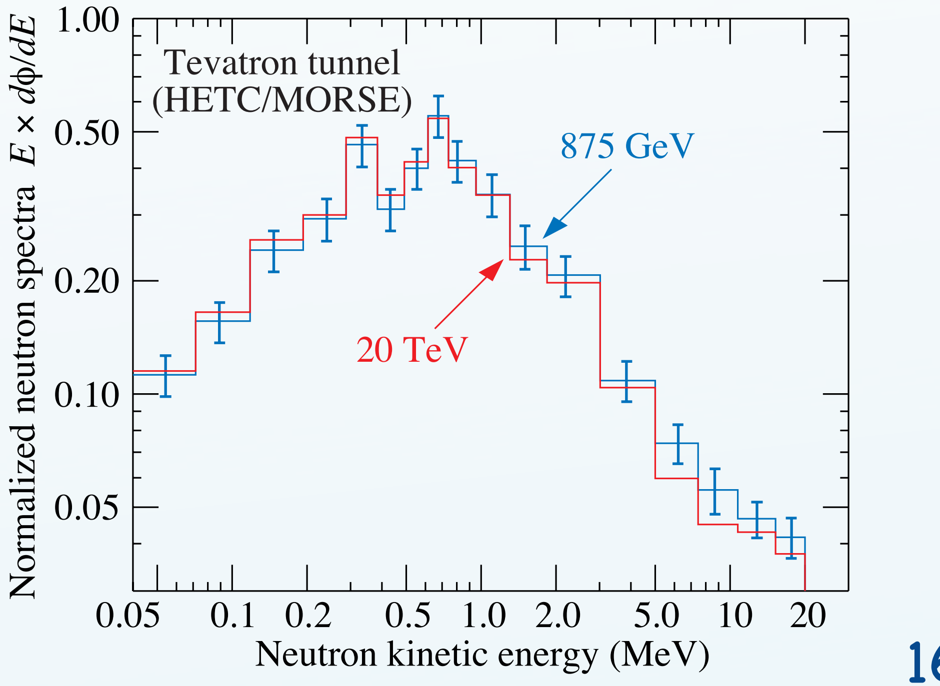
WE'LL SEE THIS AGAIN!

A necessary aside for later in the talk:
The concept of the "universal" spectrum.

"Most of the energy is eventually deposited by the ionization of very low energy particles - billyons and billyons of them.
"And the relative energy distributions are the same, no matter the species or energy of the initiating hadron."

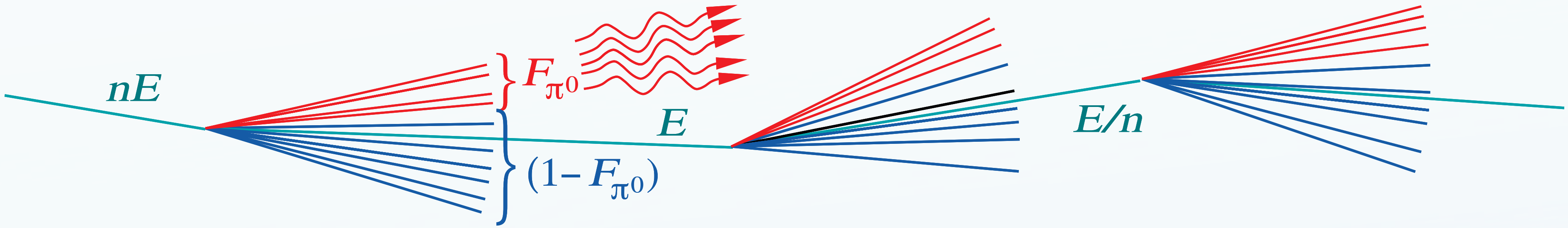
WE WILL USE THIS TWICE





All that is pretty non-controversial, but now I'll go further out on a limb:

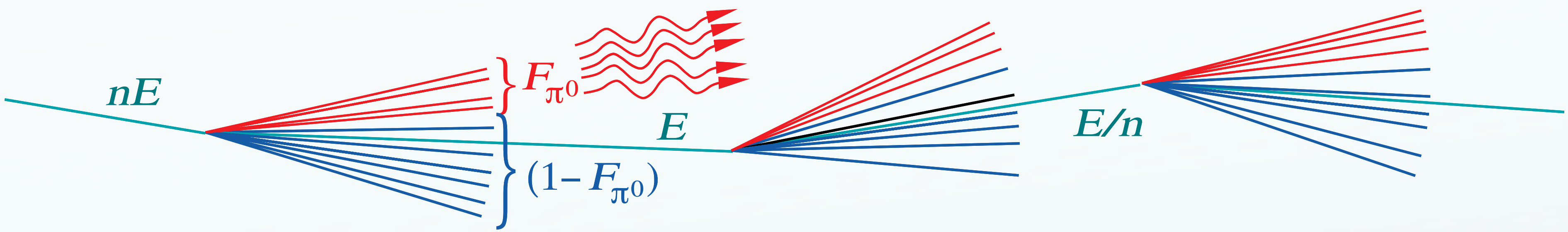
In each step, a mean fraction F_{π^0} of the secondaries are π^0's; they decay and are out of the game.



The hadronic activity $A(nE)$ produced by a hadron with energy nE is equal to the sum of the activities produced by its non-π^0 daughters

Equivalent measures of hadronic activity $A(nE)$:

- Stars with $E > XX$ MeV
- Track length
- Radioactivation
- Ionization energy deposit
- Nuclear gamma rays
- . . .



$$A\left(nE\right) = \sum_{\text{daughters} \neq \pi^0} A\left(E_i\right)$$

Hadronic activity *A(nE)*:

$$A\,(nE) = \sum_{\text{daughters}\neq\pi^0} A\,(E_i)$$

$$\approx \left(1 - F_{\pi^0}\right) nA\,(E)$$

OK, here's the big approximation

Hadronic activity *A(nE)*:

$$A\left(nE\right) = \sum_{\text{daughters}\neq\pi^0} A\left(E_i\right) \approx \left(1 - F_{\pi^0}\right) nA\left(E\right)$$

Aha! This is just the equation for a power law!

$$A\left(E\right) = K E^m$$

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$$A(nE) = \sum_{\text{daughters}\neq\pi^0} A(E_i)$$
$$\approx (1 - F_{\pi^0})\, nA(E)$$

Aha! This is just the equation for a power law!

$$A(E) = KE^m$$

. . . so we can plug in and solve:

$$1 - m = \frac{\ln(1/(1 - F_{\pi^0}))}{\ln n}$$

π^0 fraction in one collision
Isotopic spin argument: 1/3
Monte Carlo: closer to 1/4

$$1 - m = \frac{\ln\left(1/\left(1 - F_{\pi^0}\right)\right)}{\ln n}$$

Hadron multiplicity sort of goes as $\ln E$, so $\ln n$ is not very sensitive to energy. Say n in the range 6–7

So: m should be in the range 0.82 to 0.87
→ It is ultimately an experimental number.

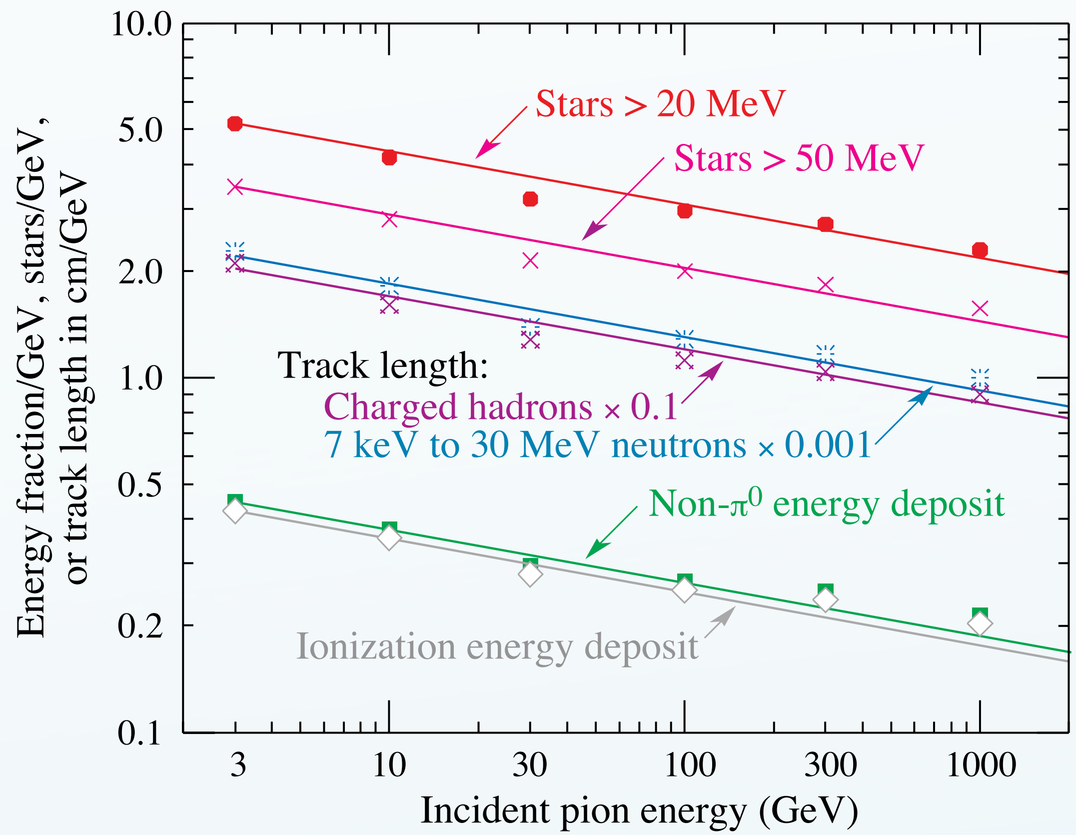
So: How well does it work?

Protons on iron (FLUKA)
Lines have slope 0.85-1

I have a love-hate relationship with Monte Carlo programs---

I do not like Monte Carlo's at all
I think my brain is much too small
I do not like them at CERN or SLAC
I won't use them when I go back
I do not like them after lunch
But I've sometimes used them in a crunch

--- but my helpful friends* are experts



*Tut, Fran, Alberto, Alfredo, Tony, P.K., Nikolai, Hannes, Graham, Sergei, . . .

And what's this got to do with π/e?

It's convenient to let the hadronic energy be the "activity:"

$$E_h = KE^m$$
$$= E\,(E/E_0)^{m-1}$$
$$\boxed{f_h = E_h/E = (E/E_0)^{m-1}}$$

MEMORABLE

E_0 is just a scale factor.

For physical reasons it should be a sort of threshold for multipion production, about 1 GeV

The Monte Carlo's verify this

CAUTION #1: Don't expect the power law to work much below 5 or 10 GeV

CAUTION #2: Remember the thing is approximate

And what's this got to do with π/e?

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As usually stated,

electron response ("e") = eE

pion response ("π") = $(e f_{em} + h f_h)E$

And with our approximation,

$$\text{“}\pi/e\text{”} = 1 - [(1 - h/e)/E_0^{\,m-1}]\, E^{m-1}$$
$$\text{“}\pi/e\text{”} = 1 - a\, E^{m-1}$$

But remember those miserable nuclear gamma rays!

Their energy fraction is $f_h \, f_\gamma$

function of E

constant, via "universal spectum theorem"

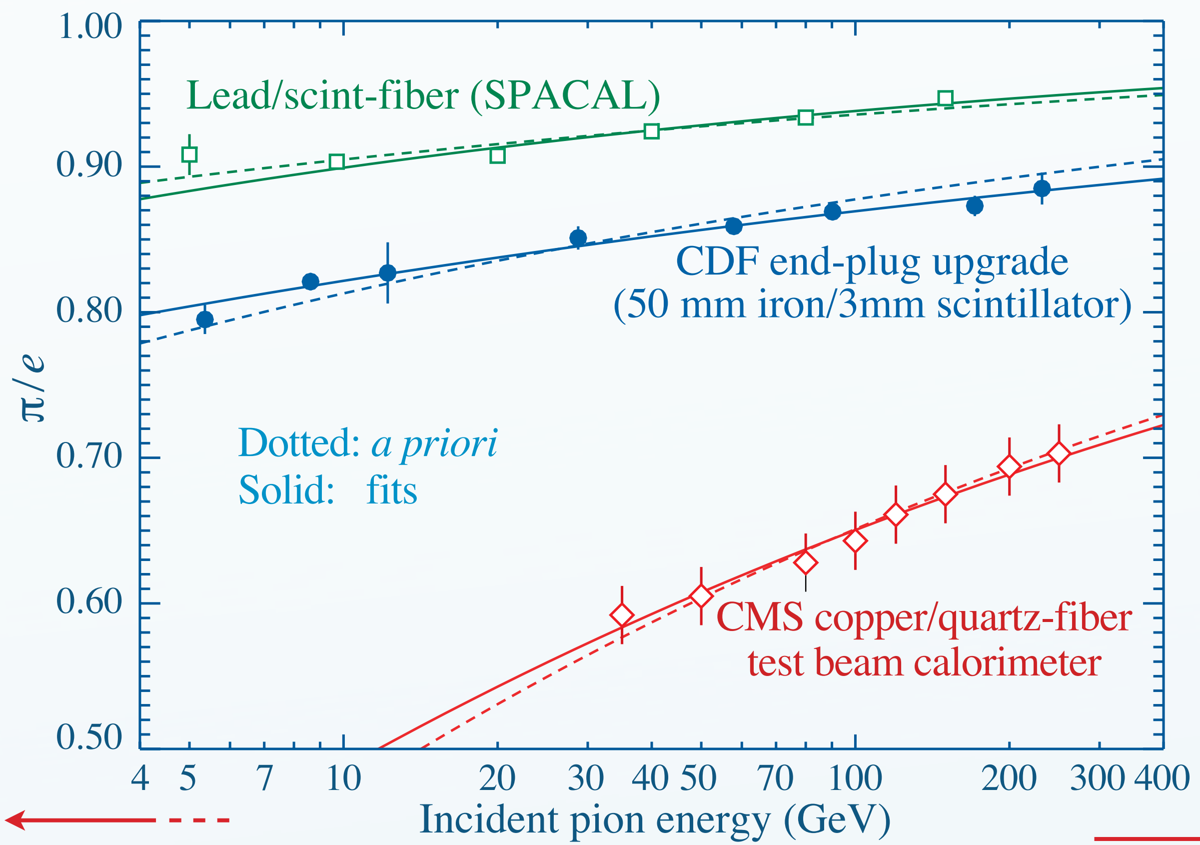
We have to move $f_h \, f_\gamma$, so that it is detected with efficiency e rather than h. Turns out

$$\text{“}\pi/\text{e”} = 1 - [(1 - h/e)(1 - f_\gamma)/E_0^{\,m-1}]\, E^{m-1}$$

$$\equiv 1 - a\, E^{m-1}$$

And this, calorimety fans, is ALL you can ever measure in a test beam.

A small sampling of fits to experimental (test beam) data:

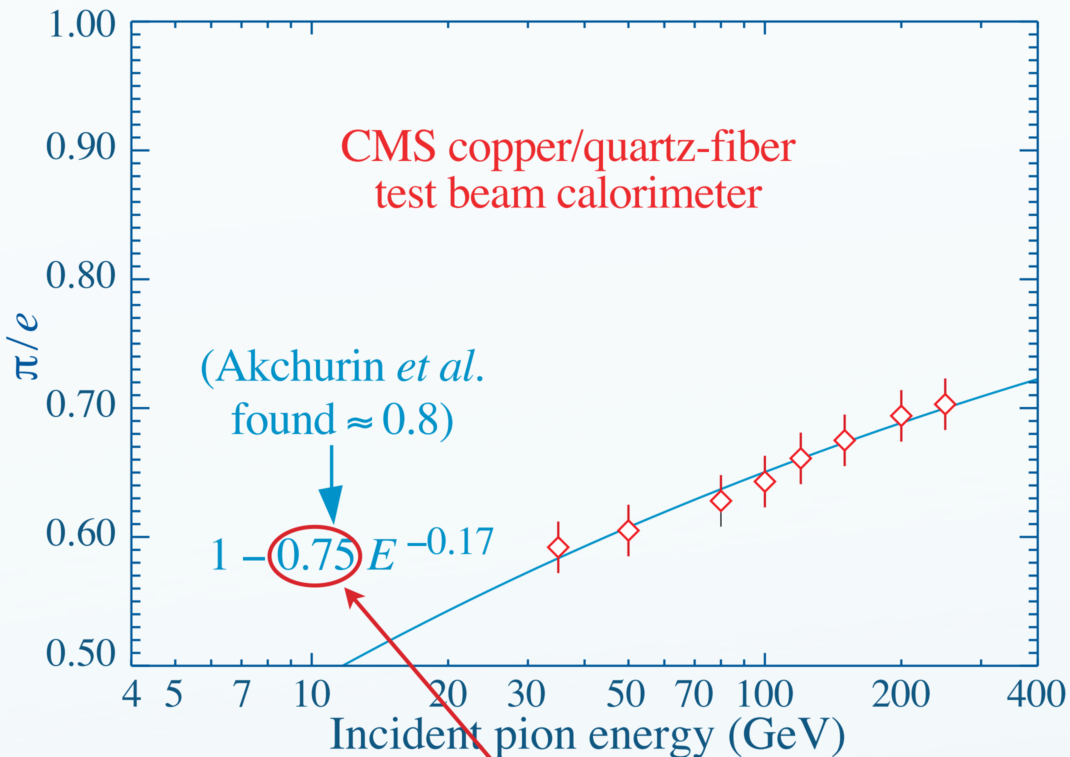


Power law no good

$\pi/e \to 1$ as $E \to \infty$

(DØ values are too close to 1.00 to be interesting)

Data from the CMS forward calorimeter prototype (QFCAL) are particularly interesting:



Assembly of the CMS forward calorimeter

$(1 - h/e)(1 - f_\gamma) = 0.75$ to 0.8 for $E_0 = 1$ GeV

$\Rightarrow$ if $h/e \approx 0$ (as it ought to be), then

f_γ = 20% to 25% of the hadronic energy

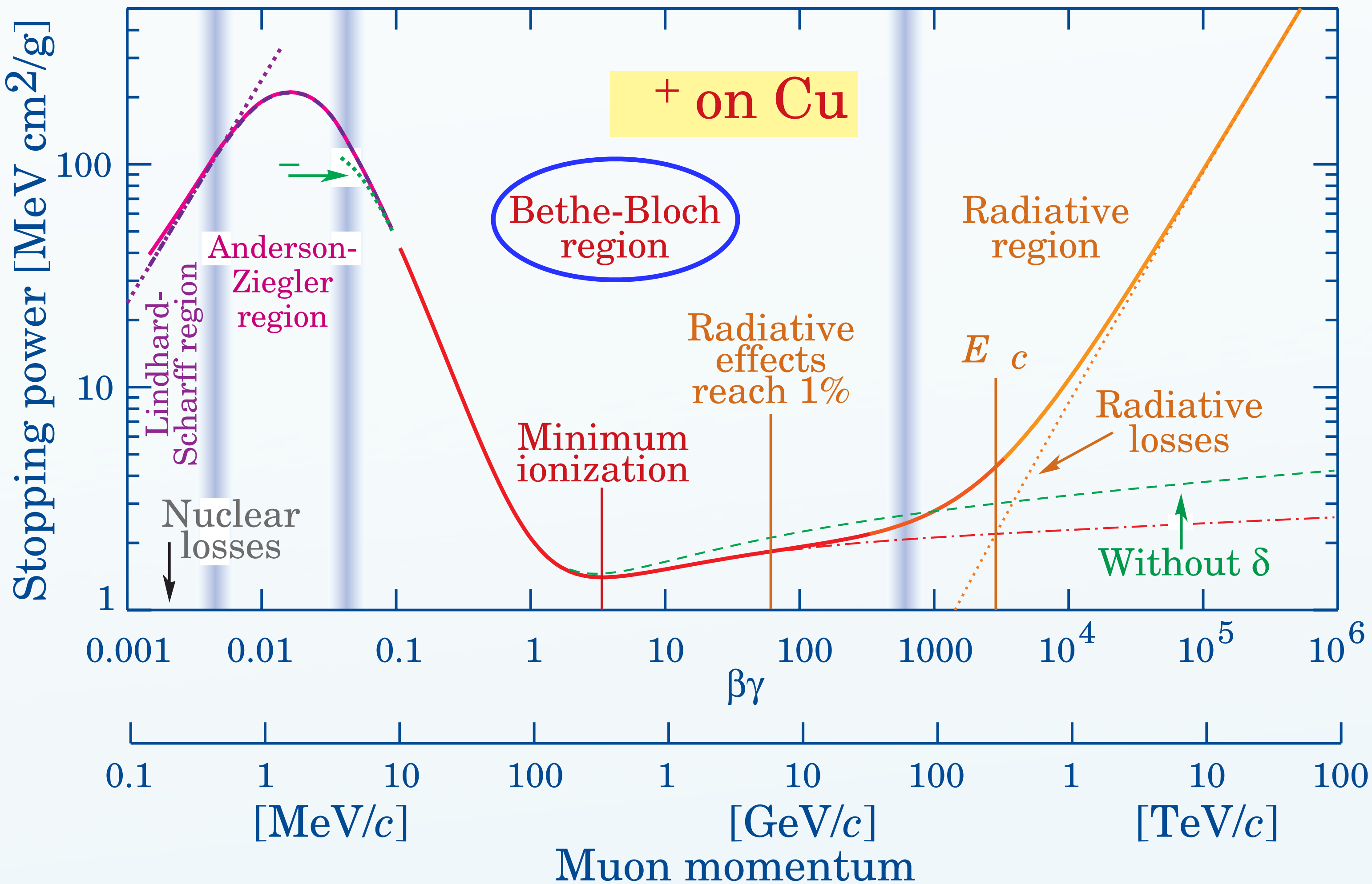
The promised big detour about $-dE/dx$ (7 slides)

It is relevant to calorimeter calibration with muons, which is described diversely and usually incorrectly.

> "The expression dE/dx should be abandoned; it is never relevant to the signals in a particle-by-particle analysis"

-- Hans Bichsel [NIM A 562 (2006) 154-197 *dE/dx* detour continued--

You learned all this at your mother's knee
(at least about the Bethe-Bloch region)



dE/dx detour continued--

In obtaining the Bethe-Bloch formula, one finds cross sections for two regions, depending on the approximations used:

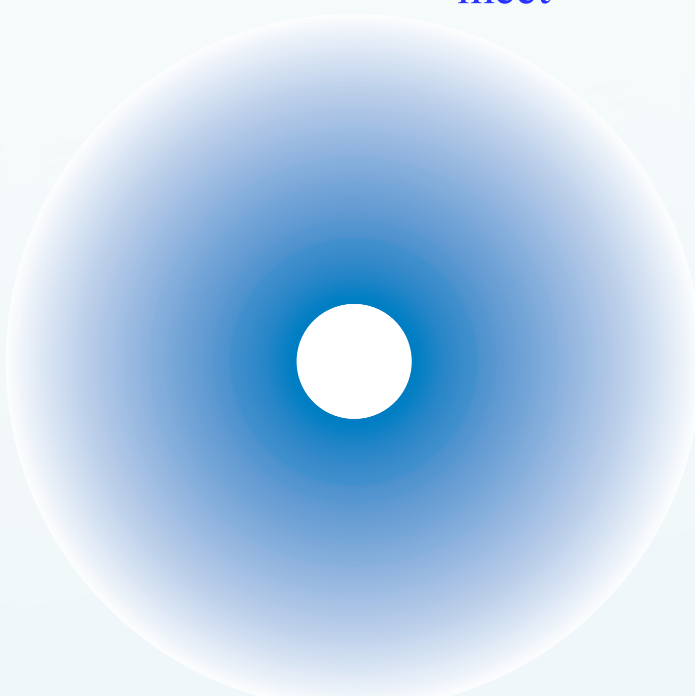
Small energy transfer, large impact parameters

Large energy transfer, small impact parameters

$$\left|\frac{dE}{dx}\right| = \left|\frac{dE}{dx}\right|_{\rm low} + \left|\frac{dE}{dx}\right|_{\rm high}$$

Below $T_{\rm meet}$*

Above $T_{\rm meet}$*

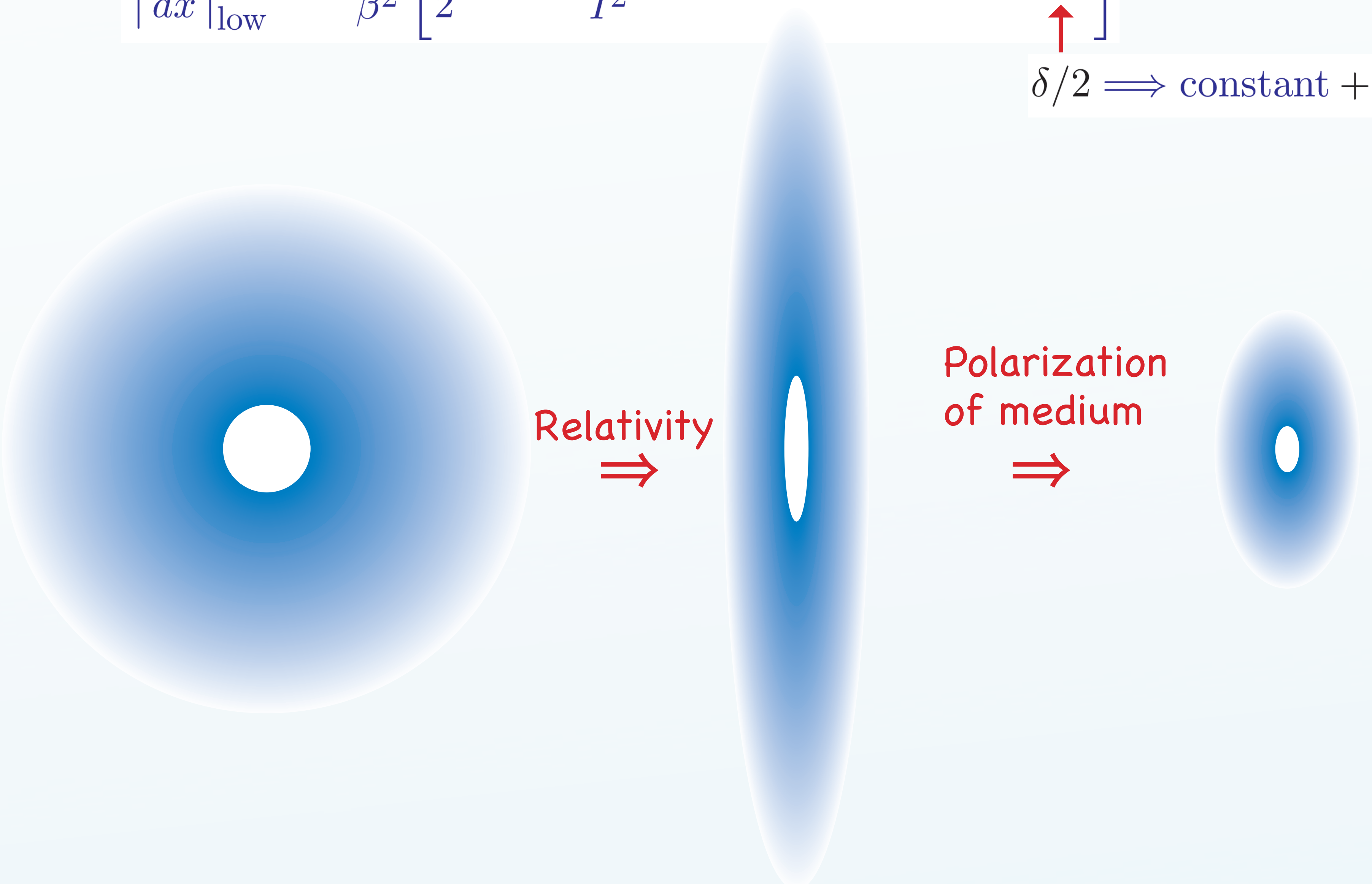


*The joining energy $T_{\rm meet}$ is of the order of atomic binding energies, but things are really more complicated.

dE/dx detour continued--

$$\left|\frac{dE}{dx}\right|_{\rm low} = C\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_ec^2T_{\rm meet}}{I^2} + \ln\beta\gamma - \beta^2/2 - \delta/2\right]$$

$$\delta/2 \Longrightarrow \text{constant} + \ln\beta\gamma$$



dE/dx detour continued--

As a final step, divide the close collision part of dE/dx at some $T_{\rm cut} < T_{\rm max}$, where $T_{\rm max}$ is the maximum possible energy which can be transferred to an electron in one collision

$$\left|\frac{dE}{dx}\right|_{\rm high} = C\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{T_{\rm max}}{T_{\rm meet}} - \beta^2/2\right]$$

$$= C\,\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{T_{\rm cut}}{T_{\rm meet}} - \frac{1}{2}\beta^2\frac{T_{\rm cut}}{T_{\rm max}}\right] \quad + \quad C\,\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{T_{\rm max}}{T_{\rm cut}} - \frac{\beta^2}{2}\left(1 - \frac{T_{\rm max}}{T_{\rm cut}}\right)\right]$$

High-energy contribution to the restricted energy loss

$\Longrightarrow$ no γ dependence

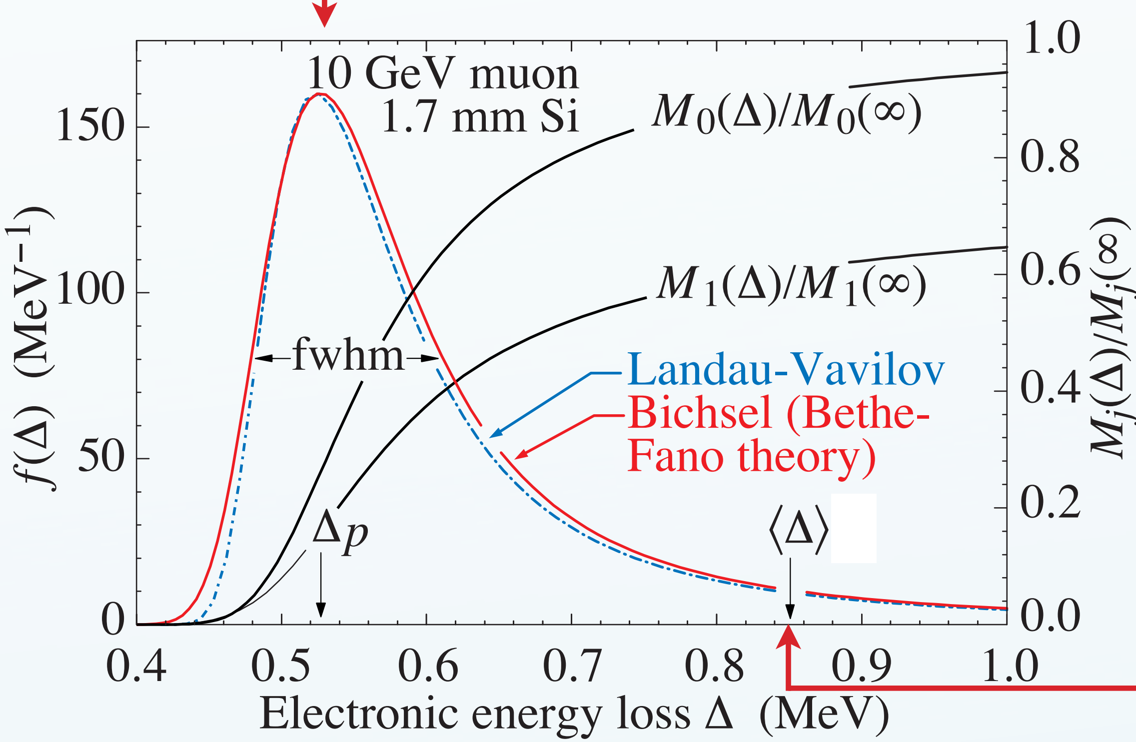
Energy in δ rays!

$\Longrightarrow$ $T_{\rm max}$ asymptotically grows as γ^2. So the relativistic rise comes ONLY from unusually high-energy collisions

. . . and in a give event there is a very, very small probability of a δ much above minimum ionization!

dE/dx detour nearly finished --

So what does this have to do with calibrating calorimeters with muons?



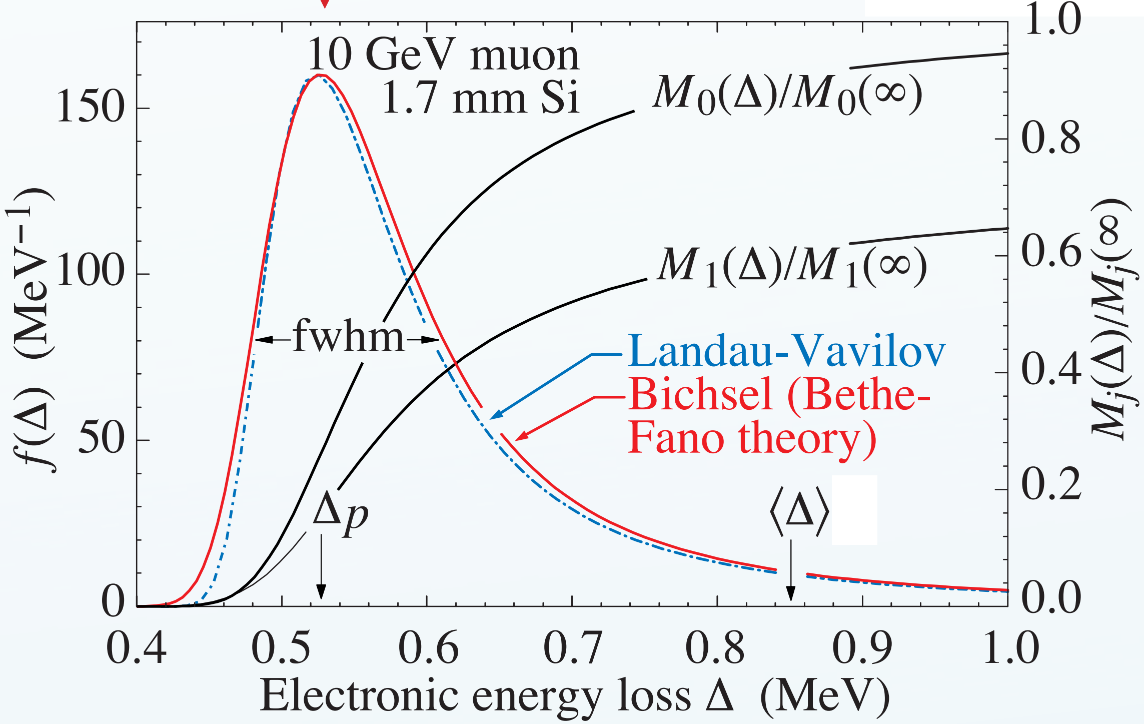
Most probable energy loss is ≈ independent of γ at "normal" test-beam energies

Bethe-Bloch -dE/dx increases with ln γ because of δ's 'way out in the tail

"The expression dE/dx should be abandoned; it is never relevant to the signals in a particle-by-particle analysis"

$$\Delta_p/x = C\frac{1}{\beta^2}\left[\ln\frac{2m_ec^2\beta^2\gamma^2}{I} + \ln\frac{C\,x/\beta^2}{I} + 0.200 - \delta\right]$$

$$\Longrightarrow C\frac{1}{\beta^2}\left[\ln\frac{2m_ec^2\,C\,x}{(\hbar\omega_p)^2} + 0.200\right]$$

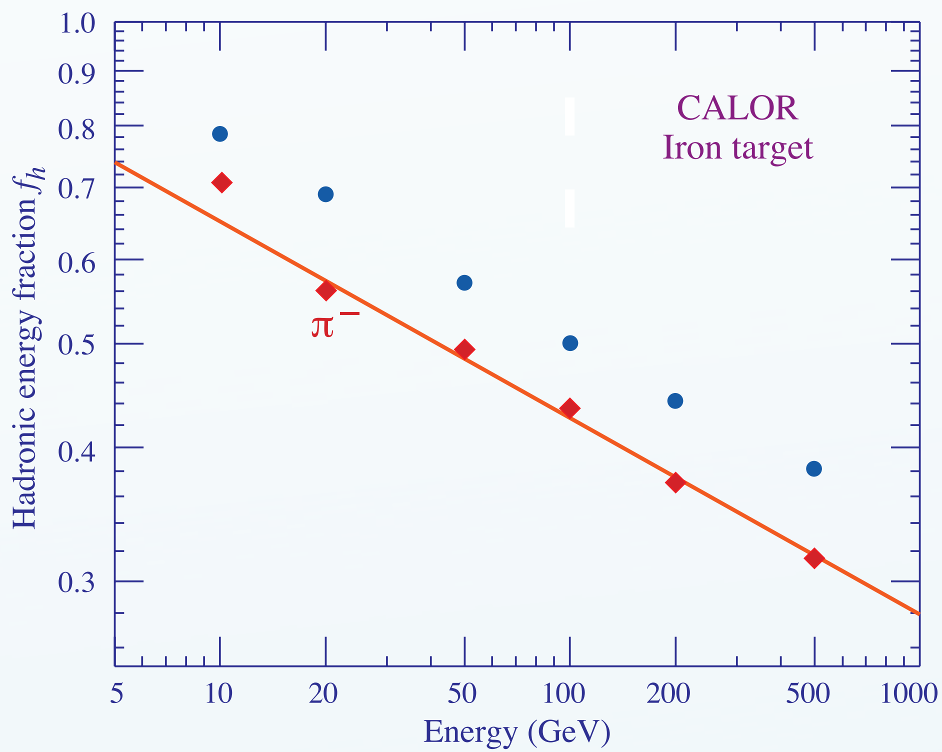


dE/dx detour finally finished!

There was a lucky mistake along the way which turned out to be a lot of fun

Tony Gabriel (Oak Ridge) was feeding me lots of HETC simulations of negative pions incident on our toy calorimeter

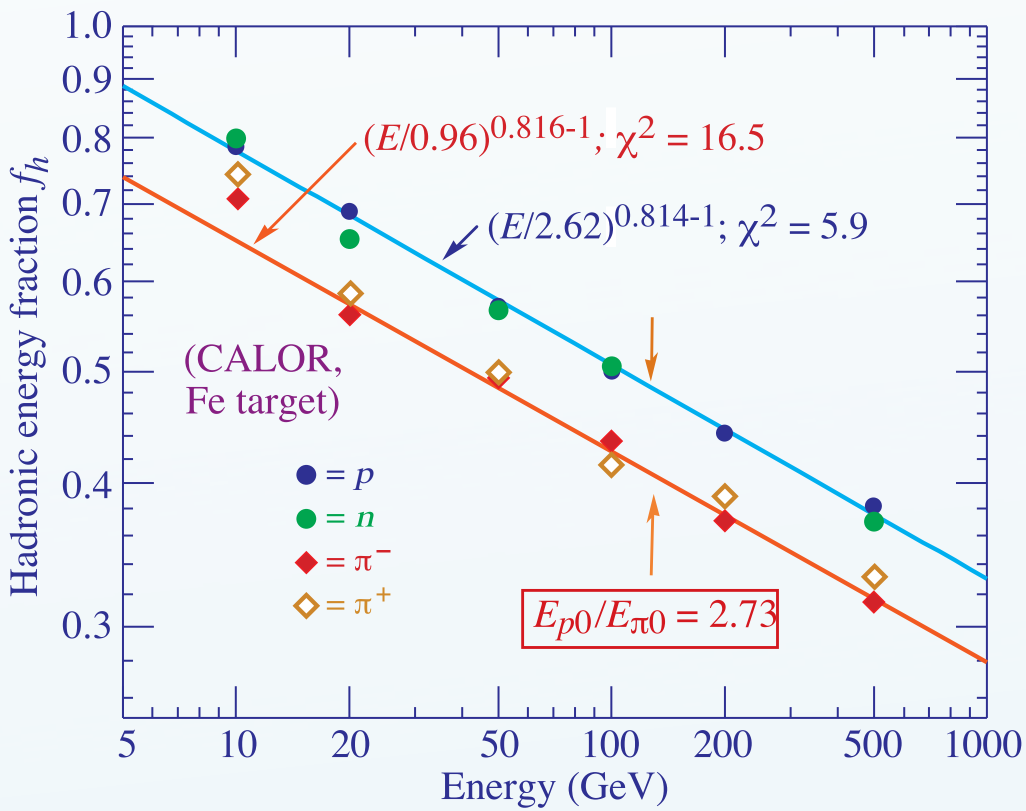
One set of runs was just nonsense:



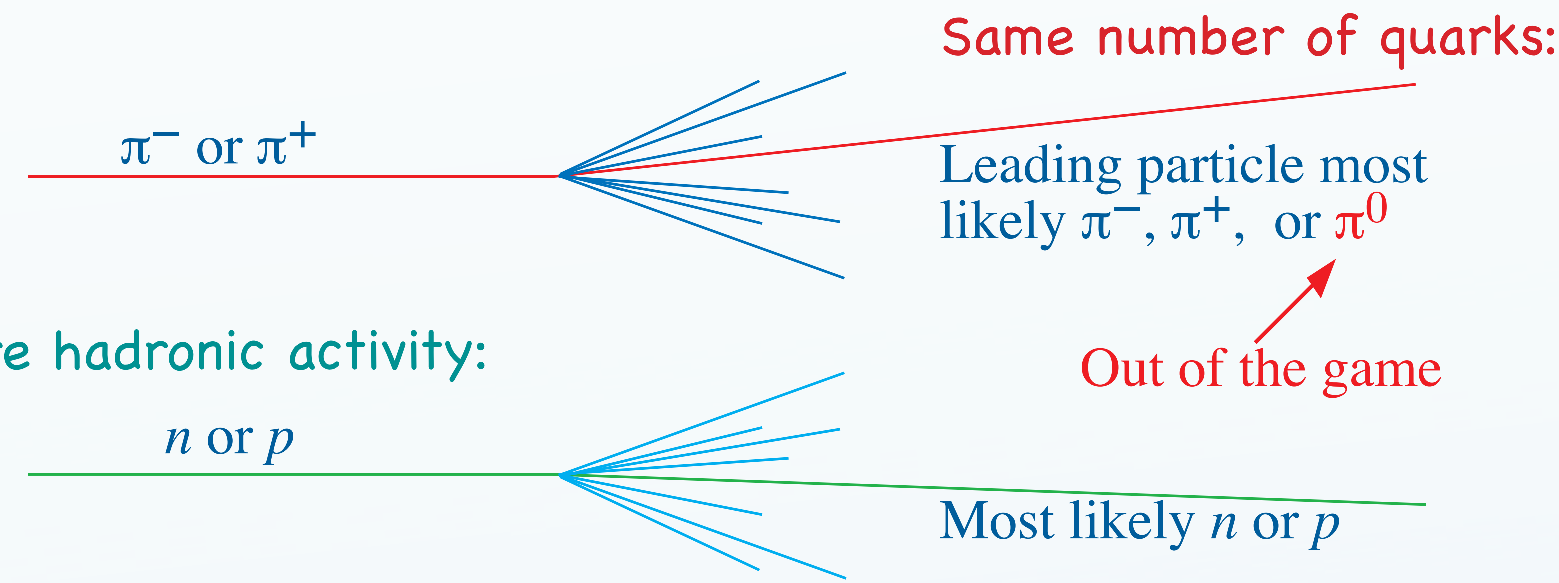
He had used incident protons, and f_h was much larger than expected.

The result turned out to be general:
The nucleon and pion responses have the same slope

→ h/e and f_γ are the same, as they must be to avoid a paradox, and as we expect from our "universal spectrum"
In the power law approximation, $f_p/f_\pi = (E_{0p}/E_{0\pi})^{1-m}$



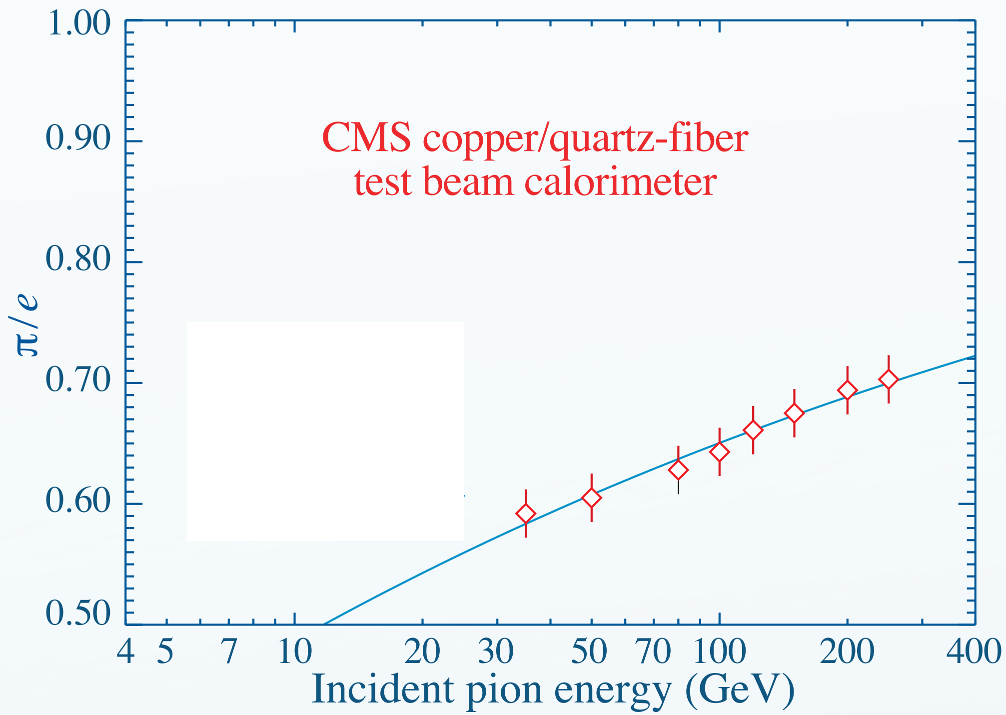
The explanation is not hard to find:



Not quite as simple as an isotopic spin argument, but, for example, at 100 GeV in Pb, CALOR says f_π/f_p should be about 0.84. For Fe, 0.76.

Hadronic fractions

Experimental verification came from "the world's worst calorimeter," the CMS copper/quartz fiber test-beam calorimeter



CMS: testing fibers for HF1

Only Cherenkov light was observed
-- barely any hadronic signal!

The CMS forward calorimeter group (QFCAL) observed that the response was in fact different for pions and protons

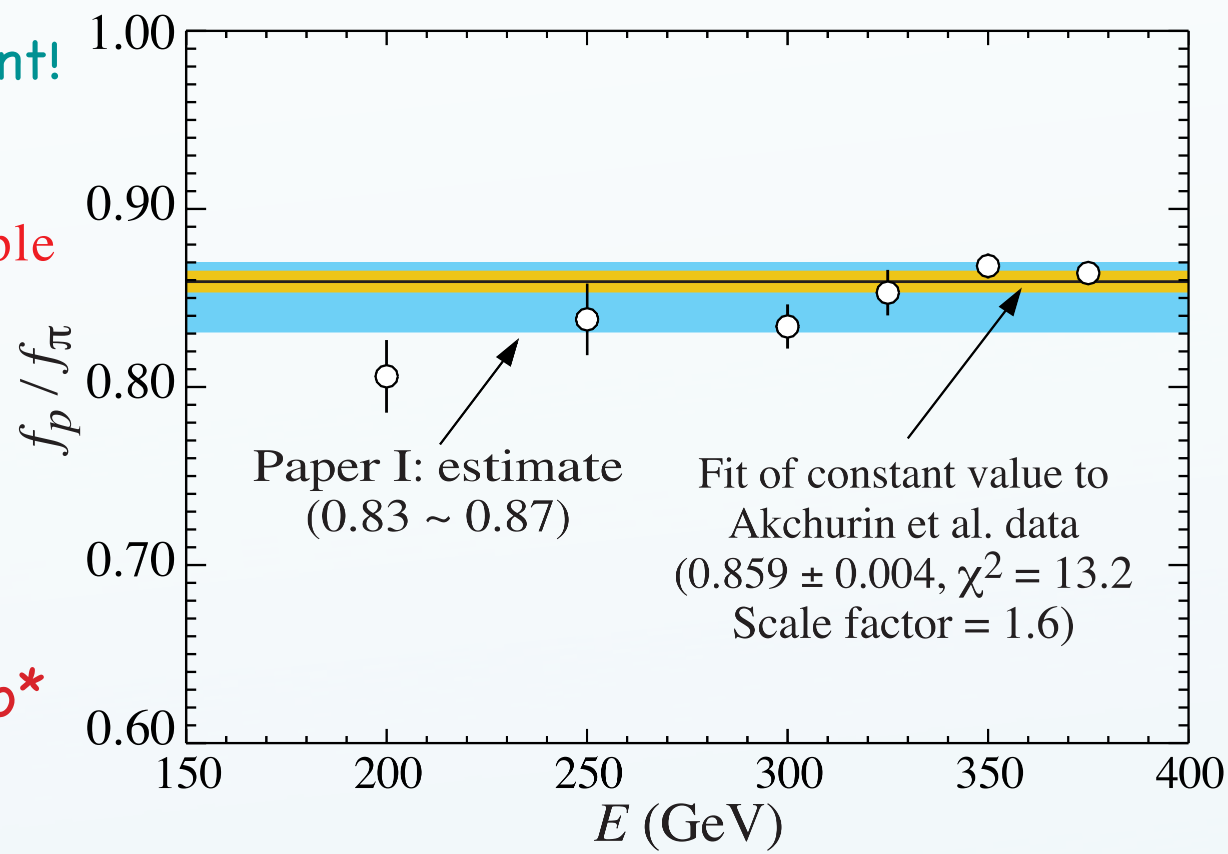
$$f_p/f_\pi = \frac{1 - p/e}{1 - \pi/e}$$ E independent!

$$= (E_{0p}/E_{0\pi})^{1-m}$$

$$= 2.75^{-0.15}$$ in this example

The scale energy for nucleons is higher than for pions -- as we expect.

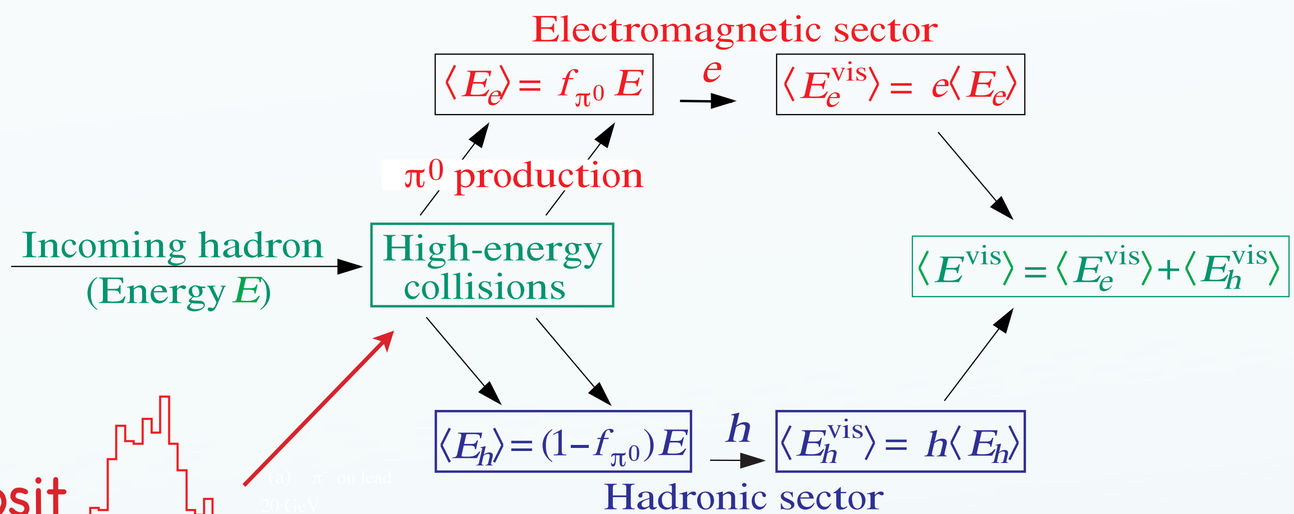
We can determine neither $E_{0\pi}$ nor E_{0p} but their *ratio* can be found!



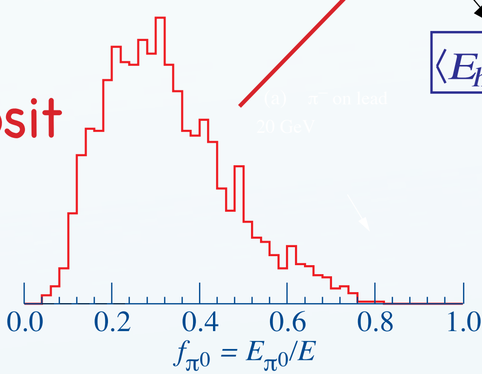
Is the slope real? (Very hard to separate positive pions and protons in the experiment)

Resolution is limited by design and by physics limits.

How can the latter be addressed?



Fluctuations in π^0 energy deposit



Here something has been done!

Fluctuations in neutron energy deposit are really, really important too!

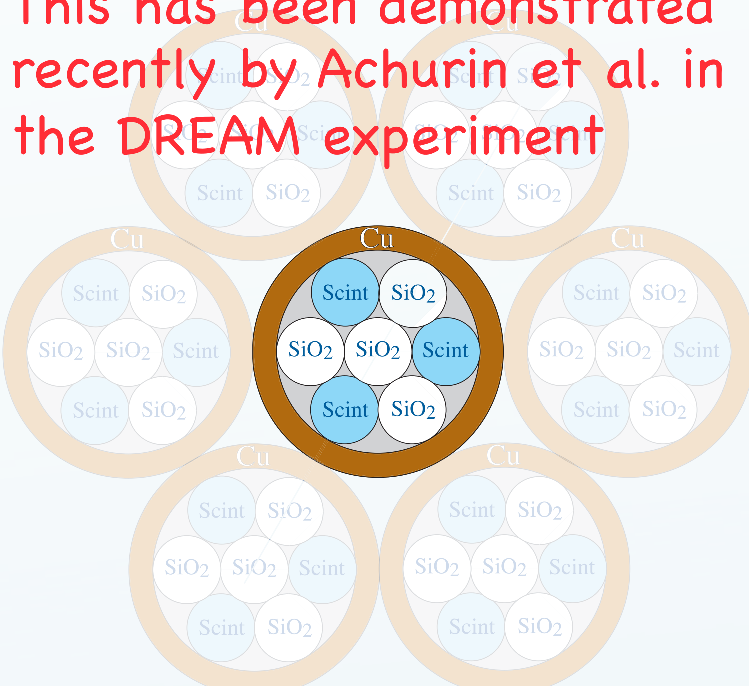
Build a calorimeter with two independent readouts with as much h/e contrast as possible!

The idea of a dual readout calorimeter has been around for a long time, at least as far back as Paul Mockett (1983)

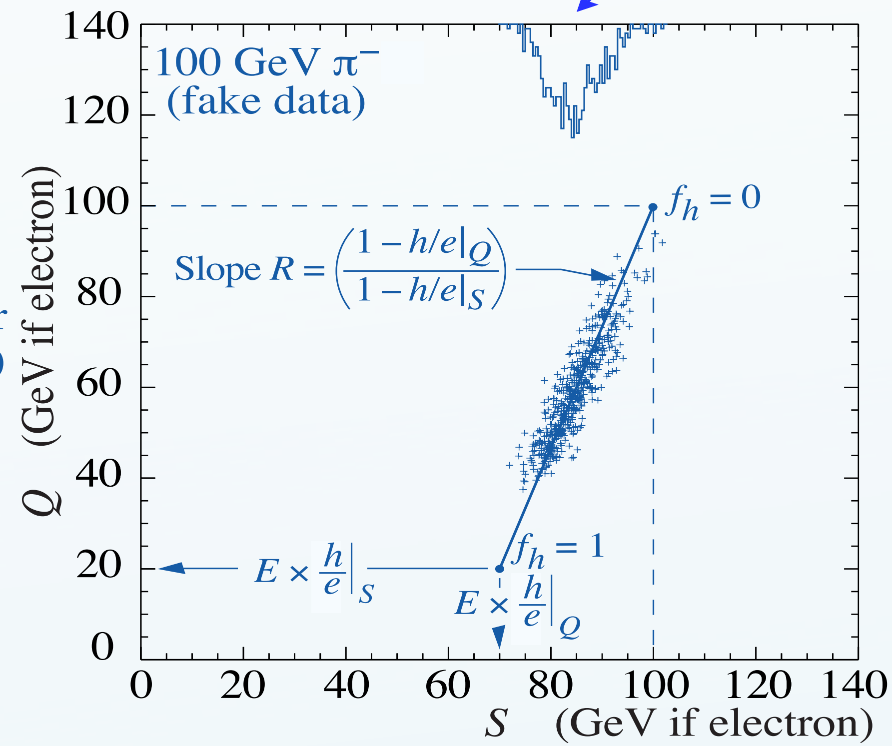
Build a calorimeter with two independent readouts with as much h/e contrast as possible!

The idea of a dual readout calorimeter has been around for a long time, at least as far back as Paul Mockett (1983)

This has been demonstrated recently by Achurin et al. in the DREAM experiment



Usual projection



$a = (1 - h/e)$* for each channel can be measured in the usual way (finding the E dependence of the π/e), or by fitting the slope R of Q vs S at one energy.

Then the data for each event can be corrected:

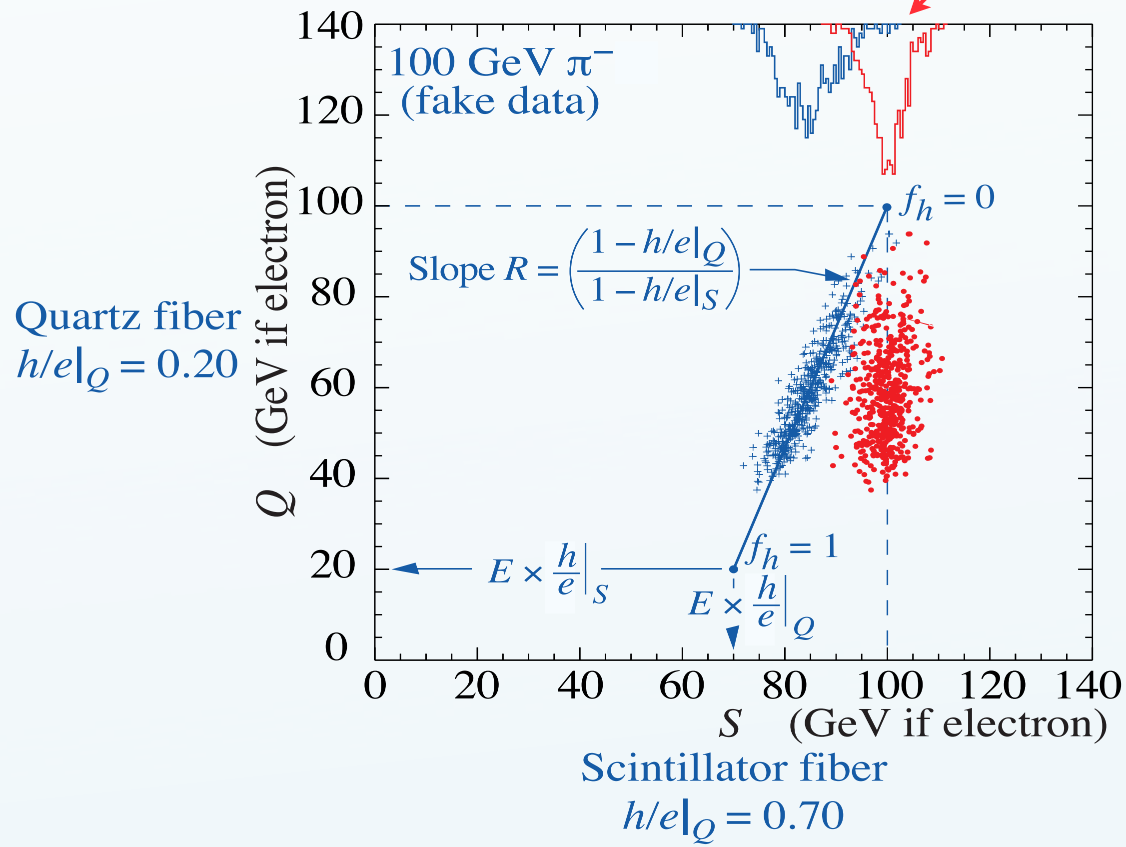
Slope

Scintillator response

$$E_{\text{corr}} = \frac{RS - Q}{R - 1}$$

Cherenkov response

Much improved!

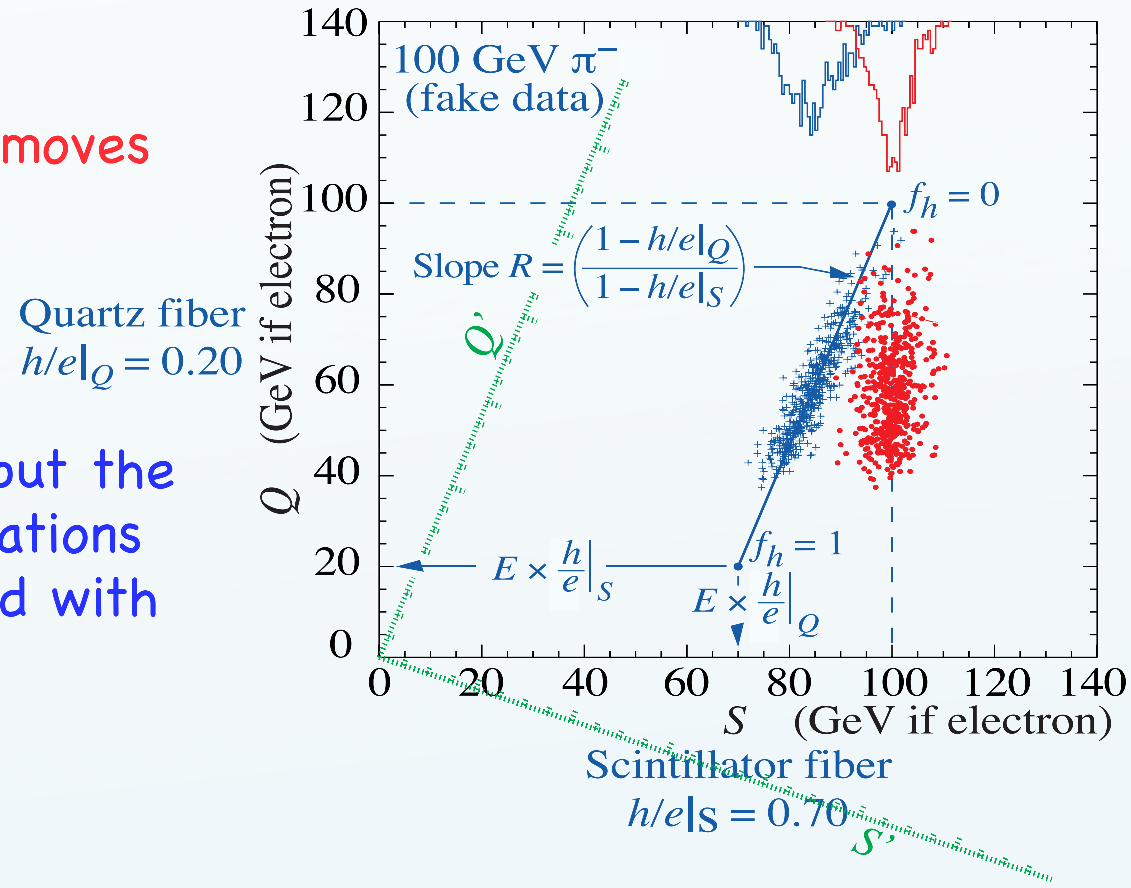


*The other factors in a seem to cancel when R is calculated

Or you can imagine transforming the data to a rotated coordinate system. This turns out to be algebraically identical.

Either way, this essentially removes the constant term.

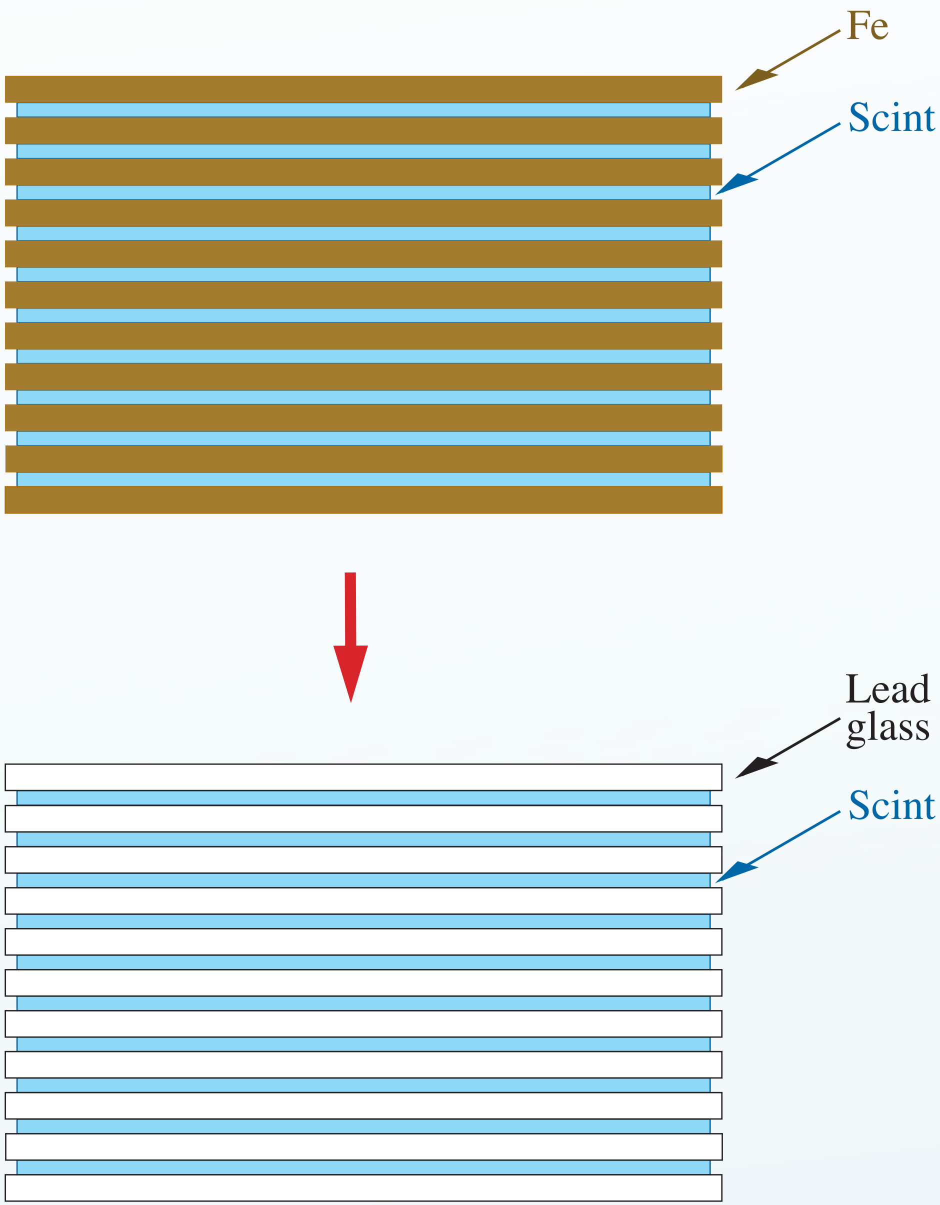
Resolution is much improved, but the neutron energy deposit fluctuations still make it lousy as compared with an EM calorimeter



A dual readout calorimeter automatically means twice as many PMT's

CMS forward calorimeter

But are there friendlier geometries?



Lots of ideas are afloat, this one presented at a 2006 Linear Collider Workshop by T. Zhao

Just replace iron in a Fe/scintillator tile calorimeter by lead glass!

Densities up to 5.7 g/cm are available

Of course, the stuff is frumiously expensive, so even at this stage glass/metal/scintillator structures are envisioned

The triple readout calorimeter

As Wigmans has pointed out, the real Holy Grail in this business is achievement of ideal resolution, limited only by the same factors as in EM calorimetry

Having measured f_{em} for individual events adequately, this step "only" involves measuring the neutron energy fraction as well

This is not easy. The little guys are hard to detect, they spread all over the place, detectors tend to be bulky and/or slow, etc.

Perhaps this is a good way to leave it:

"Such a result does not now seem likely or even possible; and yet the transformations which the study of physics has wrought in the world within a hundred years were once just as incredible as this. In view of what physics has done, is doing, and can yet do for the progress of the world, can any one be insensible either to its value or to its fascination?"

-- closing sentences of "A First Course in Physics," by Milliken & Gayle, 1906

The Lavoisier-Laplace Calorimeter, 1782-84

Credits:

Radiation physicists have long known about the "universal spectrum" (Moyer 1957) and the power-law dependence of f_h (Lindenbaum 1961), but somehow this has not been exploited in calorimetry. I'm indebted many, notably to Tut and Fran Alsmiller, Alberto Fasso', Alfredo Ferrari, Tony Gabriel, Nikolai Mokhov, Keran O'Brien, and Graham Stevenson.

11th International Conference on Calorimetry in High Energy Physics

My calorimetry friends have been quite zealous in trying to bring me up to speed, fill in history, supply references and data, and, above all, in correcting my errors. In addition to the above, a subset includes Nural Akchurin, Hans Bichsel, John Hauptman, and, especially, Richard Wigmans.

Thank you!

And what's this got to do with π/e?

It's convenient to let the hadronic energy be the "activity:"

$$E_h = K E^m$$
$$= E\,(E/E_0)^{m-1}$$
$$\boxed{f_h = E_h/E = (E/E_0)^{m-1}}$$

As usually stated,

$$\text{electron response} = eE$$
$$\text{pion response} = (e f_e + h f_h)\,E$$
$$\Downarrow$$

But with our approximation,

$$\Downarrow$$
$$\boxed{\pi/e \approx 1 - (1 - h/e)\,(E/E_0)^{m-1}}$$